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TITLE: MICROWAVE PROCESSING OF LUNAR MATERIALS: POTENTIAL APPLICATIONS

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MICROWAVE PROCESSING OF LUNAR MATERIALS:

POTENTIAL APPLICATIONS

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PROCESSING LUNAR MATERIALS BY MICROWAVES

by

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Microwave Processing of Lunar Materials:
Potential Applications

Abstract

The microwave processing of lunar materials holds promise for the production of either water, oxygen, primary metals, or ceramic materials. Extra high frequency microwaves (EHF) at between 100 and 500 gigahertz have the potential for selective coupling to specific atomic species and a concomitant low energy requirement for the extraction of specific materials, such as oxygen, from lunar ores. The coupling of ultra high frequency (UHF) (e.g. 2.45 gigahertz) microwave frequencies to hydrogen-oxygen bonds might enable the preferential and low energy cost removal (as H_2O) of implanted protons from the sun or of adsorbed water which might be found in lunar dust in permanently shadowed polar areas. Microwave melting and selective phase melting of lunar materials could also be used either in the preparation of simplified ceramic geometries (e.g bricks) with custom-tailored microstructures, or for the direct preparation of hermetic walls in underground structures. Speculatively, the preparation of photovoltaic devices based on lunar materials, especially ilmenite, may be a potential use of microwave processing on the moon. Preliminary experiments on UHF melting of terrestrial basalt, basalt/ilmenite and mixtures show that microwave processing is feasible.

INTRODUCTION. Many different suggestions have been made with regard to the potential use of lunar materials in space as well as in lunar applications. In broad terms, these applications may be classified as involving either structural uses or for raw material supply. In either case it generally is true that thermal processing will be needed for most of these potential applications. For such heating, the use of both ultra high frequency (UHF) 2.45 gigahertz microwaves as well as extra high frequency (EFH) microwaves between 100 and 500 gigahertz would appear to have very special advantages over other heating methods, as for example the use of focused sunlight. Some specific advantages of microwave heating are: a potential savings in processing energy for certain applications of at least an order of magnitude; a savings in processing time of an order of magnitude; the development, in particular geometries, of tailored microstructures; and the possibility of selectively heating only desired phases in rocks composed of many different minerals. Additionally, the use of microwave energy to process lunar materials offers the prospect of designing a continuous flow from the raw material to the finished product in a self-contained process. For example, large rocks could be fractured by coupling to particular species which possess relatively large thermal expansion coefficients. Once fractured, the rocks could be melted and separated into other raw materials or used directly for fabrication into simple but useful geometries, e.g. bricks. Importantly, if sufficiently high temperatures can be obtained it would be possible to decompose lunar materials substantially into their constituent elements without the need for any chemical feedstocks or further electrochemical processing.

In the following section we discuss first the principle features of the microwave heating of ceramic or mineral materials before proceeding to a specific discussion of the application of this method to lunar substances and the presentation of specific examples of microwave melted terrestrial rocks and ceramic materials.

MICROWAVE PROCESSING. Microwave processing of ceramics can be accomplished in two ways: first, by using UHF radiation to couple radio-frequency energy to defects, impurities, and H-O bonds and second, by coupling directly to the oxide lattice with EHF radiation. Depending on the composition of the lunar material, either or both of these radiation bands may be used. Additionally, lunar materials have been bombarded for geologic times by high energy photons and particles and as a result contain a high density of fossil radiation damage (Eddy, et al., 1980, McDougall, et al., 1971). It is quite possible that these radiation-induced defects will couple strongly to UHF radiation. Table I shows a list of relaxation mechanisms which will couple to both UHF and EHF radiation. Clearly, lunar materials will contain all or many of these mechanisms, depending on composition.

As an example of ceramic processing by microwaves, Fig. 1 shows the typical geometry of ceramic-glass-ceramic junctions fabricated using UHF radiation. Region II is the seal while region I and III are alumina substrates. Fig. 2 shows the same junction fabricated using conventional heating. Region I is an alumina substrate and region II is the glass seal. Note the very different microstructures that are produced. The microwave fabricated geometry is diffusion-bonded together while the conventionally heated geometry is held together by surface wetting only. The energy required to form the geometry of Fig. 1 was approximately 100 times less than that shown in Fig. 2 while the time required to complete the bonding shown in Fig. 1 was approximately 200 times less than that of

Fig. 2. Microwave heating rates of up to approximately 80% of the fusion temperature have reached 32,000°K/hour. A rapid heating rate for a conventional heating cycle would be between 20°K and 50°K per hour. The different microstructures evident when using microwave heating are due to high-temperature chemical reactions which occur so rapidly that the composition of the phases formed are not affected by the loss of reactants by evaporation. 4x5 ← Fig 1

Self-limiting temperatures have been observed in microwave heating. Initial heating followed by a downward trend in temperature is due to reactions coming to completion and forming high temperature phases which have altered dielectric properties and are thus less favorable for coupling to the UHF field. It thus appears possible that the use of EHF radiation will enable selective coupling to be achieved by tuning to particular phases in the material which have high coupling characteristics. In any case it is evident that microwave heating can be used to heat ceramic materials with extreme rapidity and with very low power consumption, compared to conventional ceramic processing techniques. 4x5 ← Fig 2

In the following section, we discuss several specific potential applications of microwave heating as applied to lunar materials.

Table I

Relaxation Loss Mechanism at 273°K	Coupling Frequency(H_z)
Ion Migration	$10^3 - 10^6$
Ionic Vibration	$10^{10} - 10^{14}$
Electronic Polarization	$10^{13} - 10^{17}$

Table II

Loss Mechanisms at 273°K	Coupling Frequency(H_z)
Conduction Losses	DC - 100
Impurities and Defects	$10^6 - 10^{10}$
Valence to Conduction Band	$10^{11} - 10^{17}$
Ion Jump Mechanisms	$10^3 - 10^6$

POTENTIAL APPLICATIONS. It is well known that UHF microwaves at 2.45 gigahertz couple strongly to water. It is also well known that the lunar materials which have been examined to date appear to be completely desiccated. The possibility exists, however, that some moisture may exist in permanently shadowed lunar polar regions (Watson, et al., 1961; Urey, 1967; Werner, et al., 1967) and both Japanese and American lunar missions may be designed to detect such moisture by reflected radar or other methods. Presumably polar moisture would be of an adsorbed nature and would not be actual ice. Assuming a water content of 10ppm, to heat the entire quantity of rock from -100°C to + 100°C requires more than 10,000 times as much energy as that needed to heat the water alone. Neglecting the energy cost of the required material handling, and assuming both the coupling of 2.45 GHz to water and the generation of these microwaves to be 50% efficient or better, approximately 7 liters of water a day could be obtained in 24 hours from the power produced by 10 square meters of solar cells having 10% efficiency. Material handling costs may in fact be small if the fossil hydrogen (and concomitant oxygen) were removed by a portable microwave unit and the resulting water vapor collected as ice after recondensation on a cold collecting plate.

It is also important to note that 40% by weight of lunar soils is, typically, oxygen (Mason and Melson, 1970). The extraction of this oxygen by microwave heating would be of enormous utility in the long-term support of any lunar base. The energy cost per unit weight of oxygen would be expected to be much greater than that for the extraction of water due to the relatively high energy associated with metal-oxygen bonds. However, the required mass of lunar rock per kilogram of oxygen produced would be more than four orders of magnitude less than that required in the case of oxygen with others of the most common lunar elements-- Si, Fe, Ca, Ti, Al, and Mg, are sufficiently strong that it would require temperatures of many thousands of degrees to produce the direct decomposition of lunar materials. Such temperatures can be reached with focused sunlight as well as by using microwave heating techniques, especially by means of EHF coupling directly to the appropriate metal-oxygen bonds of the mineral lattice. It is also possible, however, that microwave heating might only be needed to reach temperatures high enough to cause melting, after which decomposition to produce both oxygen as well as metallics could be achieved by means of electrochemical decomposition of the molten rock. Focused sunlight methods of melting or decomposition could, of course, be only usable during the lunar day whereas microwave melting, if powered from a nuclear source, would be continuously operable. As has been mentioned, it is to be expected that either UHF or EHF microwaves may preferentially couple to and selectively affect particular phases. In the making of brick-like materials, in which only a small fraction of either crystalline or glassy phase material need be liquified, such selective coupling could be expected to both lower the total energy requirement and aid in the development of tailored microstructures.

It is also possible to speculate that useful photovoltaic properties might be achievable using selected lunar minerals together with appropriate processing. The photovoltaic properties of elemental and compound semiconductors are, of course, well known. It is less widely known, however, that many minerological materials may also show certain semiconducting properties. In particular, such defect-semiconductors can show well defined optical band gaps. The band-gap of synthetic ilmenite has been measured to be 2.58 ev, for example. Based on band-gap considerations alone, therefore, the theoretical efficiency of solar cells based on such ilmenite could be as high as 11% (Loterski, 1956). Of course, the very poor transport properties of such defect semiconductors would make it very unlikely that anything like this level of efficiency could be reached. Nevertheless, the possibility of producing photovoltaic devices of low efficiency but also low cost using native lunar materials deserves mention. In such a possibility, the use of microwave heating with its possibility of coupling to selective phases could have useful processing advantages.

As an application of the fore going concepts, UHF heating with 2.45 Mhz microwaves has been used to produce a brick-like materials using both terrestrial basalt and an ilmenite-rich terrestrial rock. The basalt was not selected at random, but was chosen because of its similarity in many components to lunar low-titanium olivine basalts, as shown in Table III. This analogy is, of course, imperfect because of the considerably lower Fe and Cr contents, and higher water, Na, K, and P content that is common to terrestrial basalts in comparison to lunar mare basalts. The ilmenite-rich rock was a Norwegian sample consisting of about 75% ilmenite with hematite exsolution, and a matrix of plagioclase with minor pyroxenes, pyrite, pleonaste spinel, biotite, and olivine. Since limenite is a defect semiconductor, its resistivity is relatively low (on the order of hundreds of ohm-cm) and it couples strongly to the UHF microwave field. It has been found in this present work that a mixture of 10 weight percent of the ilmenite-rich rock and 90 weight percent of the Techado Mountain basalt can be melted sucessfully with 2.45 Mhz fields, whereas the Techado Mountain basalt will not melt by itself. The ilmenite acts, in this case, as a coupling agent and the resulting temperature rise is sufficient to cause the basalt to couple to this field also. These admixtures have also been melted using normal resistance furnaces. In as much as the temperatures produced during microwave melting could only be measured by optical means, it is not certain what temperatures were reached in the center of the melt. The surface of the basalt/ilmenite melt, however, was found to reach approximately 1200°C.

Using a standard resistance furnace, ilmenite was melted and then cooled at approximately the same rate as that used for the microwave melted material (air-quenching). Fig. 3 and Fig. 4 show the microstructures found in each case. As may be seen, there appear to be dramatic structural differences between these two melts. The minerological examination of the normally melted material (Fig. 3) shows that it is dominated by a globular admixture of 75% ilmenite (without hematite lamellae) and 15% hematite, in a glassy silicate matrix. Titanomagnetite occurs, but is very rare (0 1%). In contrast, the microwave melted material (Fig. 4) contains abundant (15%) cruciform or dendritic titanomagnetite, along with enhedral to subledral ilmenite (60%,; also without hematite lamellae) in a silicate matrix. Hematite is rare (∿ 1%). It is still unknown to what extent these differences are due to microwave versus normal melting, and to what extent the increased oxidation of the normally melted sample is due to slower heating and cooling while exposed to atmosphere. However, considerable differences between microwave and normal furnace-melted material might be expected based on the differential selective coupling of the different phases present in these melts. In the present case both normal melting and microwave melting produced a brick-like material which would clearly have utility as a structural material, particularly if produced in situ along tunnel walls.

Additionally, microwave melting could be used as a means of dust consolidation. In this case outright melting would probably not be required because dust particle agglomeration via sintering could be expected to occur at temperatures well below melting. Of course, during such treatment any fossil hydrogen would be expected to be driven off with the concomitant production of water which could, of course, be collected via the use of cold collecting surfaces. Of course, such heating of the entire mass of dust, by means of EHF microwaves, would consume far more energy than the selective coupling to the H-O bond by 2.45 GHz microwaves. In this way however, the two-fold purpose of dust agglomeration and water production would be achieved in a single operation.

CONCLUSION

Microwave heating appears to have several potential applications in the processing of lunar materials. The ability of selected microwave frequencies to couple to specific bonds appears to be especially valuable, particularly in the selective removal of fossil solar hydrogen, possibly as water, from lunar soils.

In certain applications, dense impermeable materials will be required whereas in others, as for example in extralunar radiation shielding applications, only a solid brick-like mass, whether or not gas-permeable, will be needed. In either case it will certainly be true that the ability of microwave processing to interact selectively with one or more specific mineralogic constitutents will be of immense help in preparing ceramic bodies with specific structural properties from lunar materials. Furthermore, the ability to heat, melt, or otherwise process lunar minerals with a minimum expenditure in both energy and time are extremely valuable characteristics. From these considerations, it appears that the use of microwave heating for the processing of lunar and other materials has unique and important benefits.

Table III

Similarities and differences between the Techado

Mountain Basalt and Lunar Low-Ti Olivine Basalts

	*Techado Mtn. New Mexico	Average Appolo 12 Olivine Basalt	Average Appolo 15 Olivine Basalt
SiO2	44.3	44.3	45.0
TiO_2	3.18	2.65	2.41
Al_2O_3	10.8	8.0	8.8
**FeO	12.0	21.1	22.4
MnO	0.18	0.28	0.30
CaO	10.1	8.6	9.8
Na_2O	2.10	0.22	0.28
K_2O	1.74	0.06	0.05
P_2O_5	0.88	0.08	0.08
Cr_2O_3	0.05	0.63	0.57

* Alkaline basalt from Techado Mountain, New Mexico, normalized to 100% water-free composition for comparative purposes (sample contains 2.1% H_2O).

** All iron occurs as $FeO(Fe^2)$ in lunar basalts; Fe^3 also occurs in terrestrial basalts, but the Techado Mountain sample is reported as FeO only for comparative purposes.

The average Appolo 12 and Appolo 15 15 olivine basalts are from Papike <u>et al</u>. (1976).

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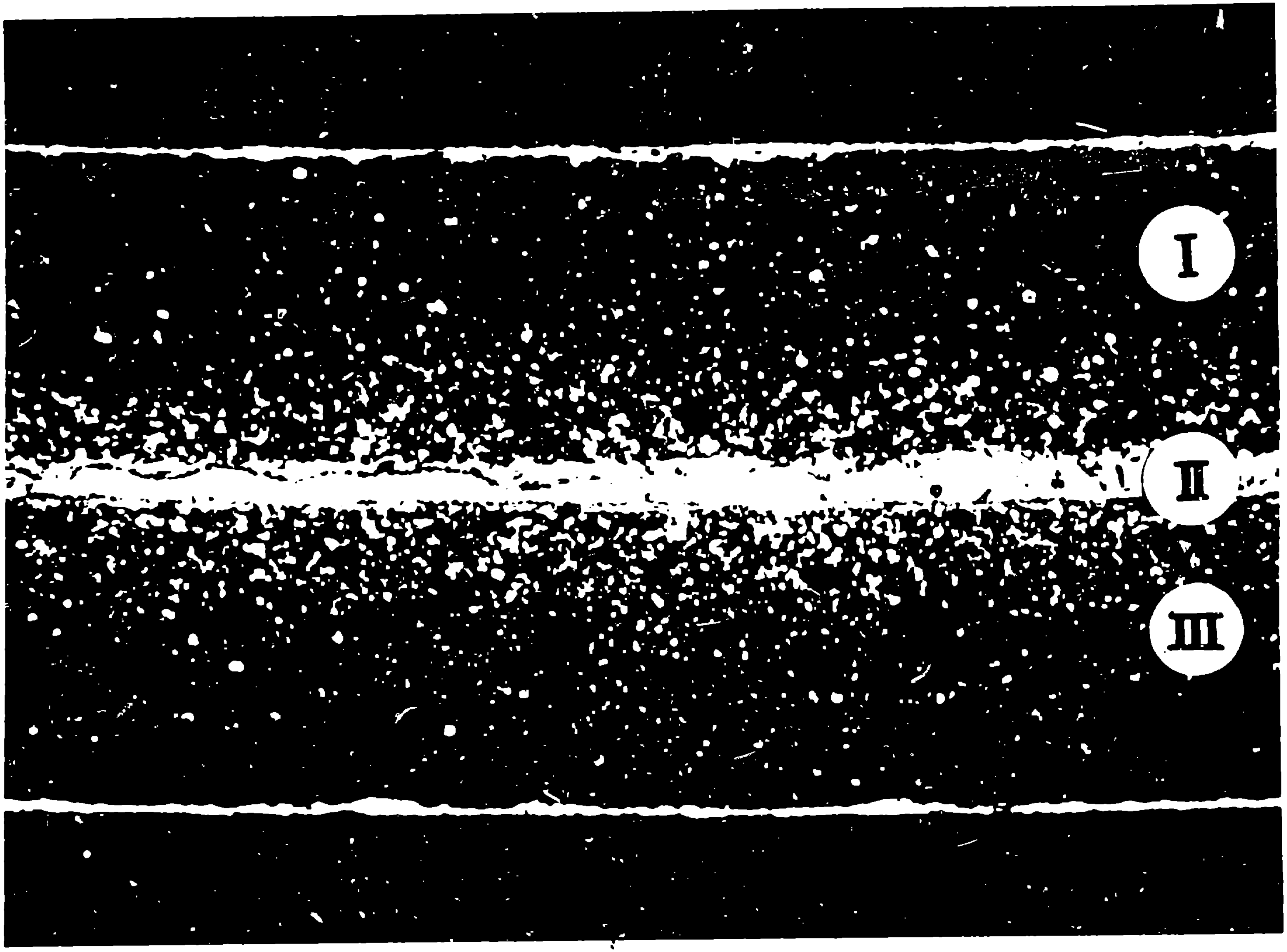
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